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RESEARCH MEMORANDUM

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OTS PRICE

XEROX $ 1.60 ph

MICROFILM $ 0.80 mf

CLASSIFICATION CHANGED TO
UNCLASSIFIED - AUTHORITY:
NASA - EFFECTIVE DATE
SEPTEMBER 14, 1962

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

April 10, 1956
Reclassified May 29, 1959

CONFIDENTIAL

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RESEARCH MEMORANDUM

EFFECT OF COMBUSTION GAS PROPERTIES ON TURBOJET-ENGINE PERFORMANCE WITH HYDROGEN AS FUEL*

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SUMMARY

In turbojet engine analyses considering hydrogen as the fuel, lack of data on gas properties in a form convenient for thermodynamic calculation has resulted in adjustment of engine cycle calculations using JP-4 fuel for the change in heat content of the fuel. This analysis compares engine performance determined in that way with the performance obtained from computations employing hydrogen as the fuel. The adjusted values from the JP-4 calculations compared with those from the hydrogen calculations as follows: Fuel specific impulse was as much as 3 percent high. Thrust per unit air flow was as much as 5 percent low. Air flow per unit of turbine frontal area was as much as 1 percent low.

INTRODUCTION

The high heating value of hydrogen has recently aroused considerable interest in its use as a turbojet engine fuel. In reference 1, lack of data on gas properties in a form convenient for thermodynamic cycle calculation resulted in adjustment of engine cycle calculations using JP-4 fuel for the change in heat content of the fuel. In particular, the values of thrust per unit air flow and the flow areas have been assumed unchanged from those for JP-4 fuel, and the values of fuel specific impulse were increased in direct proportion to the heating value of the fuel. This analysis investigates the validity of these assumptions.

For this purpose, the performance of a series of hypothetical turbojet engines was determined by thermodynamic analysis at the NACA Lewis laboratory. Two fuels were used - hydrogen and JP-4 (assumed hydrogen-carbon ratio of 0.167). Reference 2 was the source of data on properties of combustion products. A method of extrapolating the data of reference 2 to a hydrogen-carbon ratio of infinity (hydrogen as fuel) is presented in the appendix. The calculations were checked by employing the data of reference 3; essentially the same results were obtained.

The effects of using hydrogen on engine operation are also analyzed in references 4 and 5. The results of these references are not directly comparable with those presented herein, because the bases of analysis differ.

*Title, Unclassified.

SYMBOLS

c_p	specific heat at constant pressure, Btu/(lb)($^\circ$R)
f	fuel-air ratio
$\overline{H}$	lower heating value, Btu/lb
H/C	hydrogen-carbon ratio
h	enthalpy, Btu/lb
h_f	fuel enthalpy, Btu/lb
I	fuel specific impulse, (lb thrust)(sec)/(lb fuel)
T	temperature, $^\circ$R
ψ_h	$\frac{1+f}{f}(h - h_0)$ (ref. 2), Btu/lb
ψ_Φ	$\frac{1+f}{f}(\Phi - \Phi_0)$ (ref. 2), Btu/lb
Φ	$\int \frac{c_p}{T}\, dT$, Btu/(lb)($^\circ$R)

Subscripts:

0	air
0.1	hydrogen-carbon ratio of 0.1
0.167	hydrogen-carbon ratio of 0.167 (JP-4)
0.2	hydrogen-carbon ratio of 0.2
∞	hydrogen-carbon ratio of infinity (hydrogen)
c	gas $\left[CO_2 - O_2\right]$ (See p. 30 of ref. 2.)
d	gas $\left[H_2O - \frac{1}{2} O_2\right]$ (See p. 30 of ref. 2.)

ANALYSIS

Range of Calculations

Engine performance was calculated independently for use of each fuel, hydrogen and JP-4. The assigned engine operating conditions are as follows:

Compressor work, Btu/lb	75
Compressor polytropic efficiency	0.90
Combustor total-pressure ratio	0.95
Turbine polytropic efficiency	0.85
Afterburner total-pressure ratio	0.90
Primary-combustor combustion efficiency	0.98
Afterburner combustion efficiency	0.90
Exhaust-nozzle velocity coefficient	0.97
Flight Mach number	0.9, 1.5, 2.0, 2.5
Ambient temperature, ^{o}R	390

The following combinations of turbine inlet temperature and afterburner exit temperature were considered:

Turbine inlet temperature, ^{o}R	Afterburner exit temperature, ^{o}R
3000	No afterburner
2000	No afterburner
3000	3500
2000	3500

The inlet diffusers were assumed to have the following pressure recoveries:

Flight Mach number	Inlet-diffuser pressure recovery
0.9	0.950
1.5	.938
2.0	.886
2.5	.752

Fuel Properties

For JP-4, the lower heating value and the fuel enthalpy corresponding to the datum of 600° R of reference 2 were assumed to be 18,574 and 0 Btu per pound, respectively. For hydrogen, the lower heating value at the standard temperature of 25° C is 51,571 Btu per pound (ref. 6); adjustment of this value to the 600° R datum of reference 2 results in a lower heating value of 51,555 Btu per pound for use in the combustion equations of reference 2. The hydrogen was assumed to be received by the engine as a saturated liquid at 1-atmosphere pressure; reference 7 indicates that with a datum temperature of 600° R the fuel enthalpy is then -1905 Btu per pound.

The liquid hydrogen supplied to the engine was assumed to be normal hydrogen rather than the more stable para form, but the effect of this assumption on the variables to be compared is negligible.

Form of Results

The engine characteristics that were computed are: (1) fuel specific impulse, (2) thrust per unit air flow, and (3) the amount of compressor inlet air flow that can be passed through a square foot of flow area at the turbine exit if the flow is choked. The correction factor originally used for adjusting the fuel specific impulse of calculations for JP-4 fuel to that of hydrogen is $I_{0.167} \dfrac{(\overline{H} + h_f)_\infty}{(\overline{H} + h_f)_{0.167}}$ where the heating value and fuel enthalpy correspond to that at the usual datum temperature of 25° C. Under these conditions,

$$(\overline{H} + h_f)_{0.167} = 18{,}574 \text{ Btu/lb (ref. 2)}$$

$$\overline{H}_\infty = 51{,}571 \text{ Btu/lb (ref. 6)}$$

$$h_{f,\infty} = -1688 \text{ Btu/lb (ref. 7)}$$

The sum of the heating value and fuel enthalpy for JP-4 is not changed significantly by the change in datum temperature from 600° R to 25° C. For each of these engine characteristics (fuel specific impulse, thrust per unit air flow, and flow per unit area), the ratio of the value determined from the hydrogen calculations to that from the JP-4 calculations was computed. The results of these calculations are presented in figures 1 to 3.

RESULTS

Fuel Specific Impulse

The ratio of fuel specific impulses for hydrogen as fuel is shown in figure 1 to range from 0.968 to 1.004. Correction of fuel specific impulse from calculations using JP-4 may thus be in error by as much as 3 percent. For the engines investigated, the error increases with increasing temperature and, thus, with increasing fuel-air ratio. Afterburning engines have larger errors than nonafterburning ones.

Thrust per Unit Air Flow

The thrusts per unit air flow for the two fuels are shown in figure 2 to differ by 2.7 to 5.4 percent. Just as for the fuel specific impulse, greater variation is obtained with larger fuel-air ratio.

The greater thrust per unit air flow obtained from hydrogen results from a combination of two effects. Replacement of carbon dioxide in the exhaust gas by water vapor results in a reduction in the average molecular weight and thereby an increase in exhaust jet velocity for any given exhaust nozzle pressure ratio and inlet temperature. On the other hand, the high heating value of hydrogen reduces the fuel-air ratio required to obtain a given combustion temperature, with the result that the mass of gas leaving the engine decreases. The reduction in average molecular weight is the predominant effect, and the thrust per unit air flow increases.

Flow per Unit Area

Changes in gas properties resulting from changing fuels affect the attainable flow per unit area at the turbine exit in a variety of ways. The low molecular weight of the products of combustion of hydrogen decreases gas density and thus tends to increase flow area. The concomitant increase in gas constant R tends to decrease the flow area for two reasons: (1) An increase in gas constant R increases speed of sound and thus the permissible gas velocity. (2) For higher values of gas constant R, the turbine pressure ratio required to drive the compressor decreases. The combination of these effects is shown in figure 3 to result in a 0.5 to 1.0 percent increase in attainable flow per unit area at the turbine exit. For a given turbine hub-tip radius ratio, the attainable flow per unit turbine frontal area is affected in the same manner.

CONCLUDING REMARKS

For several hypothetical turbojet engines, engine performance from cycle calculations using JP-4 was adjusted for the change in heat content of the fuel and compared with the performance computed for hydrogen as fuel. The adjusted values from JP-4 calculations compared with those from the hydrogen calculations as follows:

1. Fuel specific impulse was as much as 3 percent high.

2. Thrust per unit air flow was as much as 5 percent low.

3. Air flow per unit of turbine frontal area was as much as 1 percent low.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 18, 1955

APPENDIX - EXTRAPOLATION OF HYDROGEN-CARBON RATIO TO INFINITY

Equation (34) of reference 2

$$h = \frac{f}{1 + f}\left[\frac{h_c + (H/C)\ h_d}{1 + (H/C)}\right] + \frac{h_0}{1 + f}$$

can be changed to read

$$h = \frac{f}{1 + f}\left[h_d - h_0 + \frac{h_c - h_d}{1 + (H/C)}\right] + h_0 \tag{1}$$

Revision of equation (35) of reference 2 yields

$$\psi_h = h_d - h_0 + \frac{h_c - h_d}{1 + (H/C)} \tag{2}$$

Values of ψ_h are presented in reference 2 for various temperatures and for hydrogen-carbon ratios from 0.1 to 0.2. Because the properties of air and the gases "c" and "d" are independent of hydrogen-carbon ratio for any given temperature, equation (2) can be used to determine ψ_h for any selected value of hydrogen-carbon ratio, in this case for infinity, in terms of the values of ψ_h for hydrogen-carbon ratios of 0.1 and 0.2. In particular,

$$\psi_{h,0.2} - \psi_{h,0.1} = \frac{h_c - h_d}{1 + 0.2} - \frac{h_c - h_d}{1 + 0.1}$$

or

$$h_c - h_d = 13.2\ (\psi_{h,0.1} - \psi_{h,0.2}) \tag{3}$$

For a hydrogen-carbon ratio of infinity, equation (2) reduces to

$$\psi_{h,\infty} = h_d - h_0 \tag{4}$$

Substitution of equation (3) into equation (2) yields

$$\psi_h = h_d - h_0 + \frac{13.2(\psi_{h,0.1} - \psi_{h,0.2})}{1 + (H/C)}$$

and for a hydrogen-carbon ratio of 0.2, this expression reduces to

$$h_d - h_0 = 12\ \psi_{h,0.2} - 11\ \psi_{h,0.1}$$

Combination of this expression and equation (4) gives

$$\psi_{h,\infty} = 12\ \psi_{h,0.2} - 11\ \psi_{h,0.1} \tag{5}$$

Values of $\psi_{h,0.2}$ and $\psi_{h,0.1}$ read from reference 2 can thus be used to determine $\psi_{h,\infty}$ for any selected temperature.

Equation (34) of reference 2 also yields

$$\Phi = \frac{f}{1 + f}\left[\Phi_d - \Phi_0 + \frac{\Phi_c - \Phi_d}{1 + (H/C)}\right] + \Phi_0 \tag{6}$$

This expression can be modified, just as equation (1) was modified, to produce

$$\psi_{\Phi,\infty} = 12\ \psi_{\Phi,0.2} - 11\ \psi_{\Phi,0.1} \tag{7}$$

REFERENCES

1. Silverstein, Abe, and Hall, Eldon W.: Liquid Hydrogen as a Jet Fuel for High-Altitude Aircraft. NACA RM E55C28a, 1955.

2. English, Robert E., and Wachtl, William W.: Charts of Thermodynamic Properties of Air and Combustion Products from 300° to 3500° R. NACA TN 2071, 1950.

3. Keenan, Joseph H., and Kaye, Joseph: Gas Tables. John Wiley & Sons, Inc., 1948.

4. Gammon, Benson E.: Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. IV - Hydrogen, α-Methylnaphthalene, and Carbon. NACA RM E51F05, 1951.

5. Tower, Leonard K., and Gammon, Benson E.: Analytical Evaluation of Effect of Equivalence Ratio, Inlet-Air Temperature, and Combustion Pressure on Performance of Several Possible Ram-Jet Fuels. NACA RM E53G14, 1953.

6. Perry, John H., ed.: Chemical Engineers' Handbook. Third ed., McGraw-Hill Book Co., Inc., 1950, p. 244.

7. Woolley, Harold W.: Scott, Russell B., and Brickwedde, F. G.: Compilation of Thermal Properties of Hydrogen in Its Various Isotopic and Ortho-Para Modifications. Jour. Res. Nat. Bur. Standards, vol. 41, no. 5, Nov. 1948, pp. 379-475.

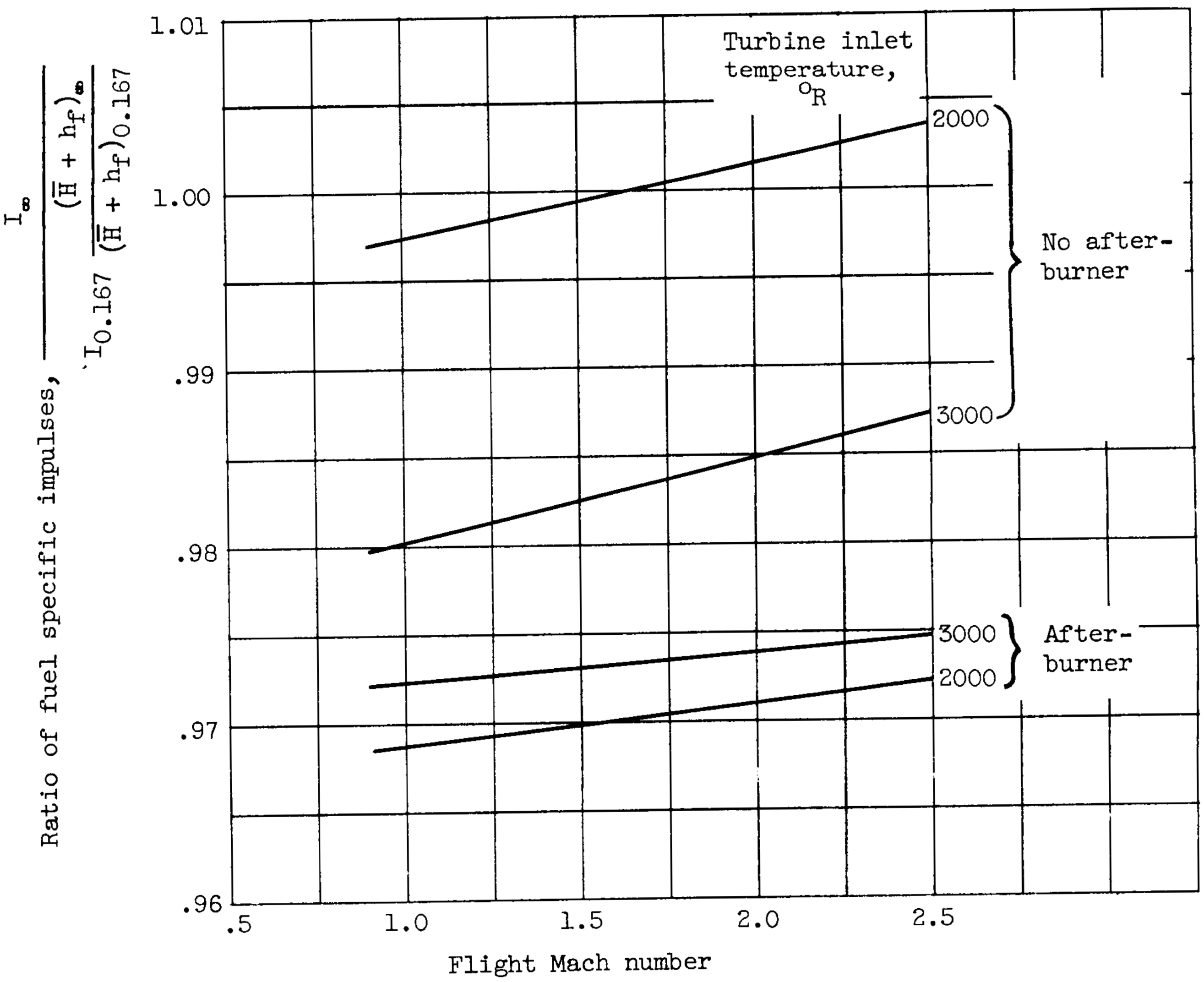

Figure 1. - Effect of gas properties on fuel specific impulse.

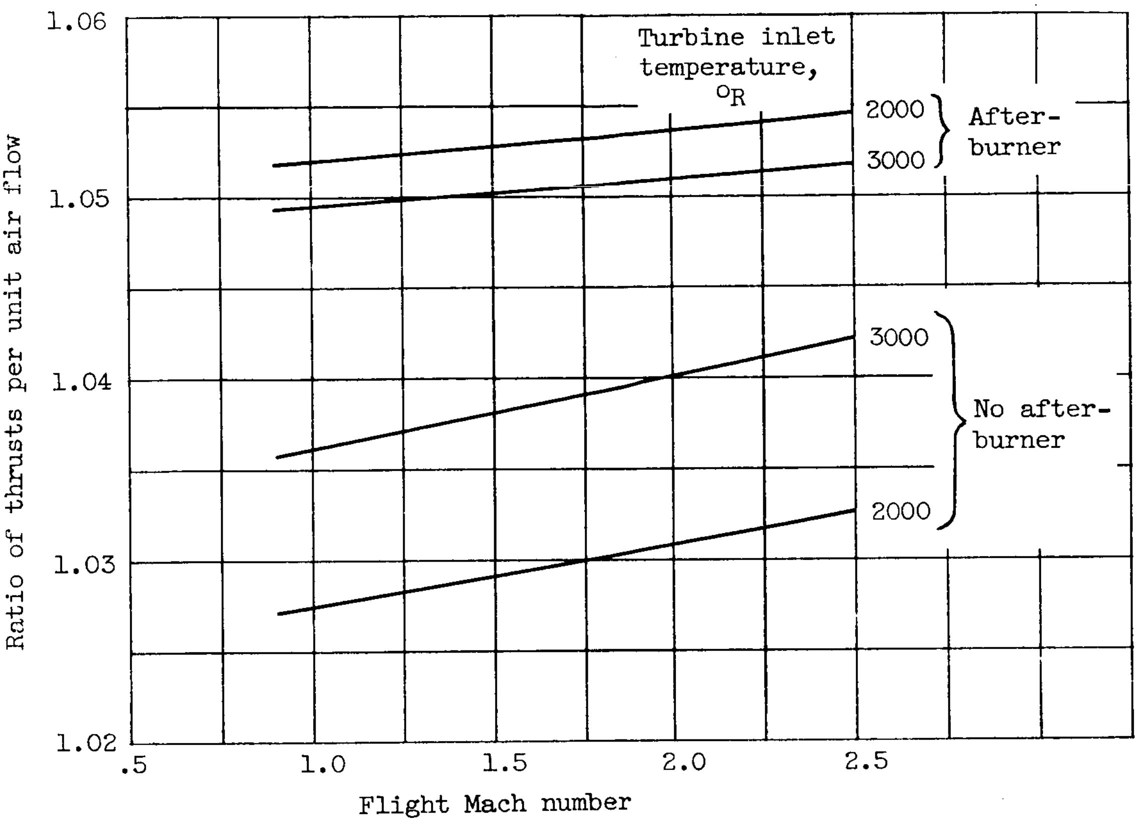

Figure 2. - Effect of gas properties on thrust per unit air flow.

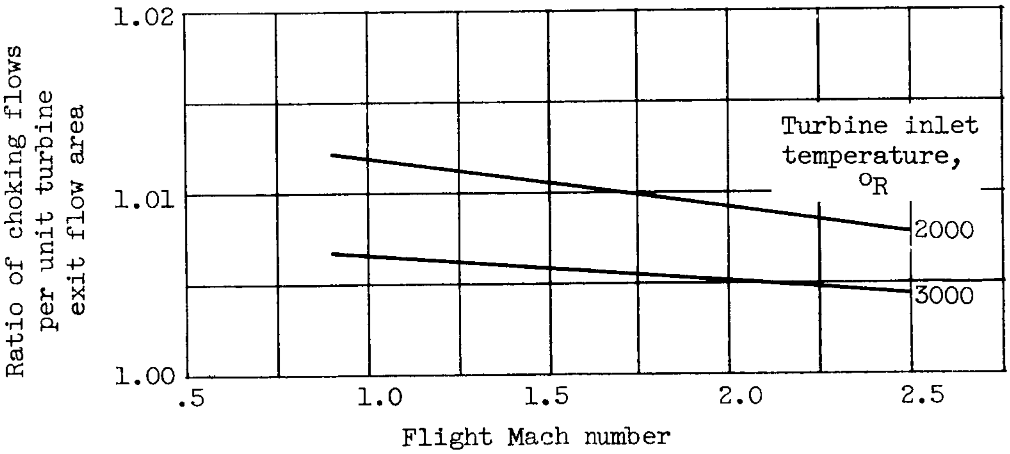

Figure 3. - Effect of gas properties on flow per unit area.